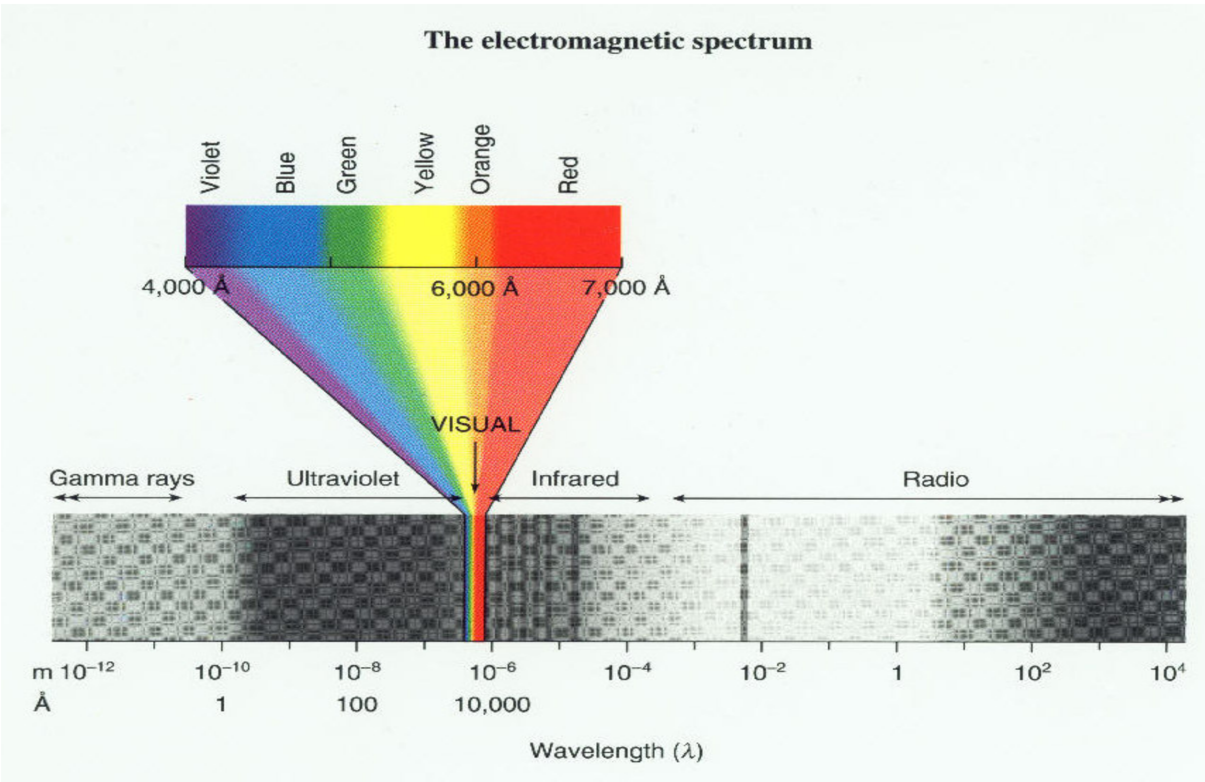
CHAPTER 3

SPECTROSCOPY and ATOMIC STRUCTURE

3-1. Introduction

Light is a phenomenon which we imagine consists of electromagnetic waves or photons. The wavelength of an electromagnetic wave is the distance between adjacent crests of a wave. It is the wavelength of radiation that determines what color the human eye perceives. Red light consists of much longer wavelengths than violet. Orange, yellow, green and blue light have increasingly shorter wavelength waves than red until we reach violet. Shorter than violet wavelengths are radiations we call ultraviolet, x-rays, and finally gamma rays. Wavelengths longer than those of red light are infrared, microwaves, and radio waves. All of these groups of EM waves comprise what is called the total electromagnetic spectrum. All EM radiations travel with the same speed through



a vacuum, which we call the speed of light, c. The value for c is approximately 300,000 km/sec. The speed of light is less for other media and depends on the wavelength.

Sir Isaac Newton was the first to demonstrate that what we observe as white light was a mixture of all visible colors and that each of these colors could not be further separated into any other colors. He carried out the first experiments in spectroscopy by studying sunlight. He is considered the father of spectroscopy. An example of a spectrum in nature is the rainbow. Here raindrops in the Earth's atmosphere sometimes act in unison to spatially separate the different colors in sunlight to form a spectrum of the Sun's light. We call this phenomenon a rainbow. Rainbow halos may also be seen around the Moon. These lunar halos are produced by a thin layer of clouds made of ice crystals. The ice crystals produce these halos much the way raindrops produce a rainbow of sunlight.

Hence, the light emitted by any star consists of a sufficient mixture of many different wavelengths or colors so that we essentially see white light. The starlight may be tinted slightly red or slightly blue, depending on which color dominates. All of this is in accordance with the black body theory of radiation. One way to determine the temperature of a star is to study how bright the component colors are in the star's light and then apply Wien's Displacement Law. To accomplish this, we must spatially separate the different wavelengths or colors and form what is called a spectrum.

We can do this for any celestial body by attaching an instrument to a telescope called a spectrograph or a spectrophotometer. These devices use either a prism or a mirror ruled with thousands of very closely spaced lines (a diffraction grating) to form a spectrum of the star's light. With the spectrophotometer, one directly measures the relative brightness of the spectrum at different wavelengths. We have seen that distribution of brightness with wavelength is given theoretically by Planck's Law. In the eighteenth and nineteenth centuries, contributions to the study of spectral were made by Fraunhofer, Kirchhoff, Bunsen, Balmer, and Angstrom.

3-2. Kirchhoff's Laws

Recall that objects that convert thermal energy into radiant energy are called incandescent bodies. In 1859, Gustav Robert Kirchhoff (1824 -1887) and Robert Busen (1811 - 1899) collaborated on carrying out a series of laboratory studies of the spectra emitted by a variety of incandescent bodies under different physical conditions and established what are now known as Kirchhoff's Laws of Spectroscopy. Kirchhoff also coined the term "black body" radiation in 1862. His 3 laws of spectroscopy are:

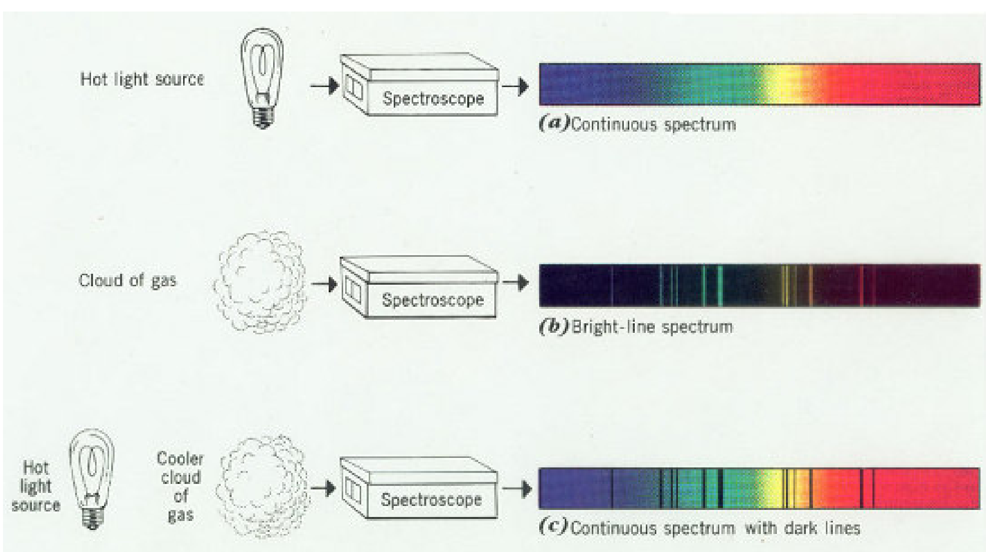
1. An incandescent solid, liquid, or gas under high pressure, emits a continuous spectrum.

This is because the atoms interact strongly with one another, thereby smearing their electron energy levels. When high pressure in a gas does this, it is called the "Stark" effect.

2. A hot gas under low pressure emits a bright line or emission spectrum.

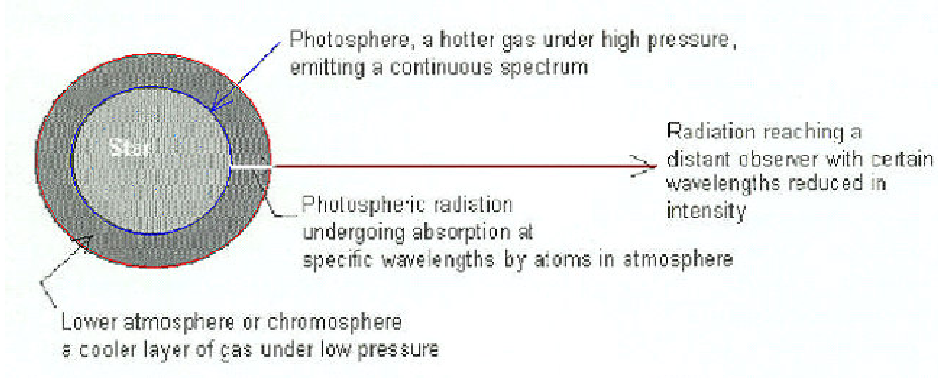
That is, the spectrum reveals radiation only at discrete wavelengths

3. When the source of a continuous spectrum is observed through an intervening layer of cool gas under low pressure, a dark line or absorption line spectrum is observed.



The production of each of these spectra is schematically illustrated in the diagram above, where the radiation coming from the light bulb is produced by a hot tungsten filament, a solid. In this diagram, it is assumed the cloud of gas producing the bright-line spectrum is hot. An important point here is that the emission and absorption lines in the spectrum are unique for the chemical composition of the gas. That is, a definite atomic species emits radiation at the same wavelengths when it is hot that it absorbs when it is cool.

Stellar spectra are somewhat different than the continuous spectrum which is described by Planckian curves, nor are they emission spectra. In fact, they are dark line spectra as described by Kirchhoff's 3rd law. The surface or photosphere of a star is a gas under high pressure. However, radiation leaving the surface or **photosphere** of a star must travel through the star's atmosphere before getting into space. The atmosphere of a star selectively absorbs radiation at specific wavelengths that correspond to energy levels in the atoms comprising the star's atmosphere. See the diagram to the right. Therefore, a star's spectrum has dips in the intensity at many wavelengths, corresponding to the light absorbed by the atoms in a star's atmosphere. These dips are very narrow and are called **"absorption lines, dark lines, or Fraunhofer lines".** Fraunhofer was the first to see and catalog such lines in the spectrum of the Sun.

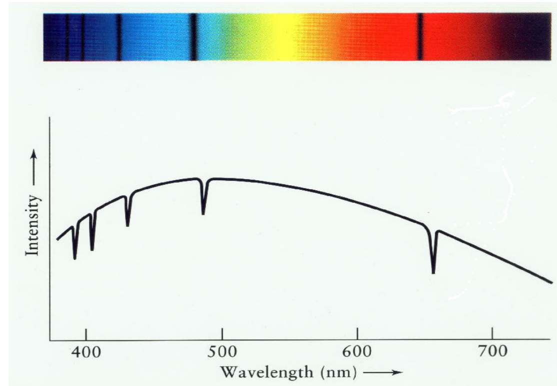


Joseph von Fraunhofer (1787-1826) was a German optician and astronomer. Fraunhofer was orphaned at age 11, which necessitated working as an apprentice to a glassmaker named Philipp Anton Weichelsberger. In 1801, the workshop in which he was working collapsed and he was buried in the rubble. The rescue operation was led by Maximilian IV Joseph, then Prince Elector and future King of Bavaria, to be known as Maximilian I. The prince entered Fraunhofer's life, providing him with books and forcing his employer to allow young Joseph time to study.

After eight months of study, Fraunhofer went to work at the Optical Institute at Benediktbeuren, a secularised Benedictine monastery devoted to glass-making. There he discovered how to make the world's finest optical glass and invented incredibly precise methods for measuring dispersion. In 1818, he became the director of the Optical Institute. In 1814, Fraunhofer invented the spectroscope, with which he discovered and cataloged 574 dark lines appearing in the solar spectrum. These were later shown to be atomic absorption lines, as explained by Kirchhoff and Bunsen. These lines are still called Fraunhofer lines in his honour. He also invented the diffraction grating and in doing so, transformed spectroscopy from a qualitative art to a quantitative science by demonstrating how one could accurately measure the wavelengths of sprectral lines. He found out that the spectra of Sirius and other first-magnitude stars differed from each other and from the Sun, thus founding stellar spectroscopy. He also developed what is now called the "German Equatorial Mounting System" for telescopes to facilitate his astronomical observations. This mounting permited a weight driven clock mechanism to compensate for the rotation of the Earth by turning the telescope around one axle aligned with the north celestial pole.

Fraunhofer's illustrious career eventually earned him an honorary doctorate from the University of Erlangen in 1822. Like many glassmakers of his era, who were poisoned by heavy metal vapours, Fraunhofer died young, in 1826 at the age of 39. His most valuable glassmaking recipes are thought to have gone to the grave with him.

There are 2 ways of recording a spectrum. A photograph of a spectrum is called a spectrogram. The top panel in the diagram to the right depicts a spectrogram for the absorption spectrum of hydrogen, which is what dominates the spectrum of an A2 star. The bottom panel is called a spectrophotometric image or tracing of the spectrogram, though it can be recorded directly using a specctrophotomer.



3-3. Atomic Theory of Radiation

In 1915**,** Niels Bohr, a Danish physicist, developed a new model of the atom based on E. Rutherford's scattering experiments, Planck's concept of the quantatization of energy and momentum, and experimental spectroscopy. This model successfully predicted the measured wavelengths that were emitted or absorbed by an atom. We now present the mathematical derivation of this model.